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Pajak

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(54) **SYSTEM, METHOD, AND COMPUTER PROGRAM PRODUCT FOR JOINT COLOR AND DEPTH ENCODING**

(71) Applicant: **NVIDIA Corporation**, Santa Clara, CA (US)

(72) Inventor: **Dawid Stanislaw Pajak**, San Jose, CA (US)

(73) Assignee: **NVIDIA Corporation**, Santa Clara, CA (US)

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G06K 9/00 (2006.01)
G06T 9/00 (2006.01)
H04N 19/597 (2014.01)

(52) **U.S. Cl.**

CPC ***G06T 9/00*** (2013.01); *H04N 19/597* (2014.11)

(58) **Field of Classification Search**

None

See application file for complete search history.

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Primary Examiner — Li Liu

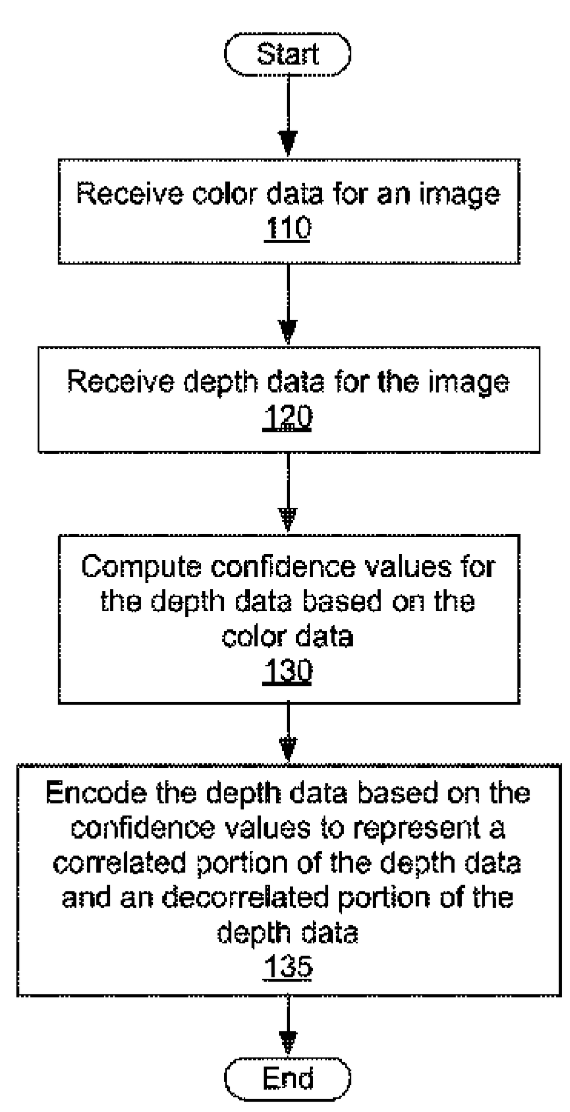
(74) *Attorney, Agent, or Firm* — Zilka-Kotab, PC

(57) **ABSTRACT**

A system and method are provided for performing joint color and depth encoding. Color data and depth data for an image is received. Based on the color data, confidence values are computed for the depth data and the depth data is encoded based on the confidence values to represent a correlated portion of the depth data and a decorrelated portion of the depth data. In one embodiment, the depth data comprises per-pixel vergence angles.

18 Claims, 7 Drawing Sheets

100



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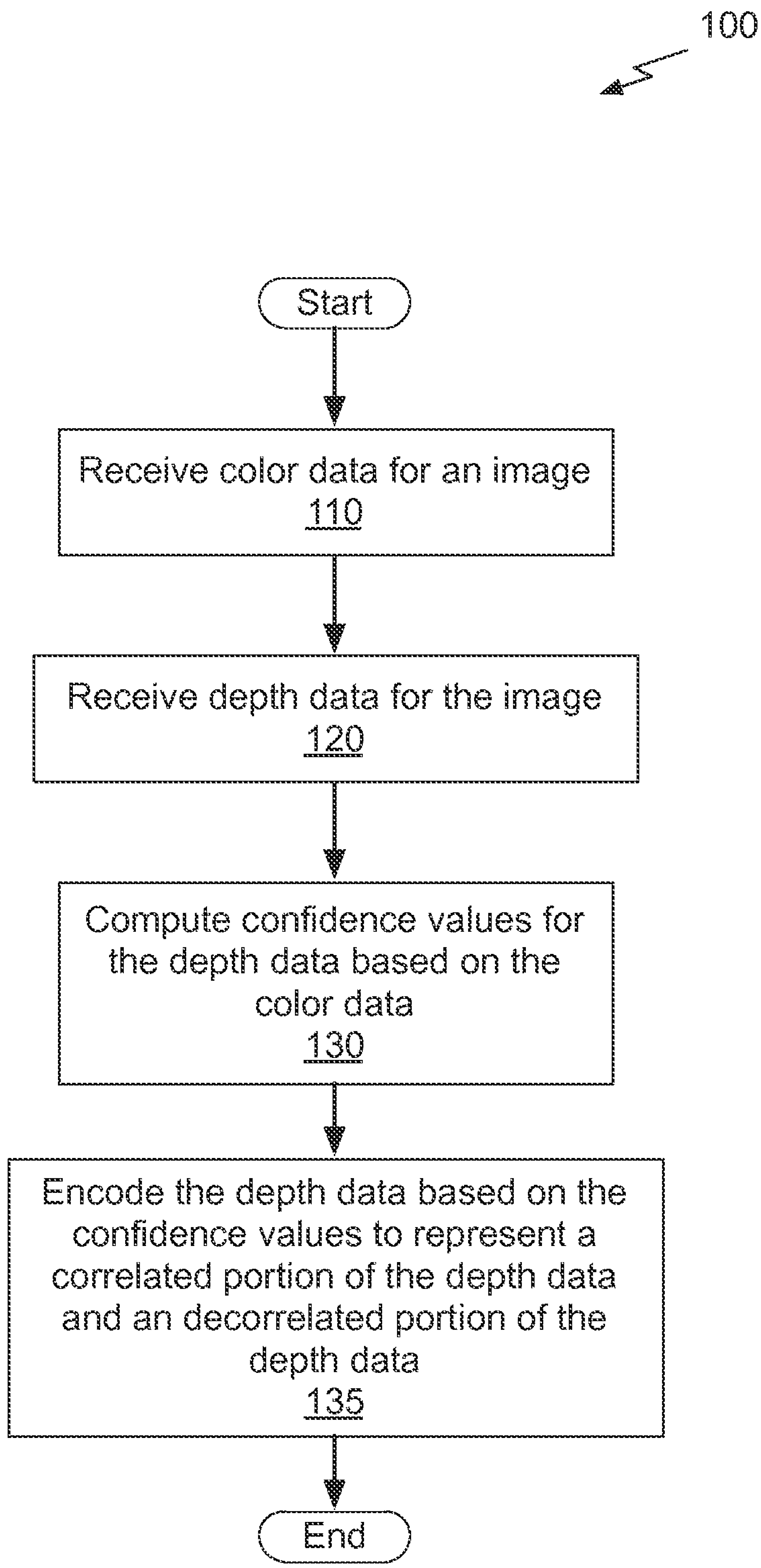
100
Start
Receive color data for an image
110
Receive depth data for the image
120
Compute confidence values for the depth data based on the color data
130
Encode the depth data based on the confidence values to represent a correlated portion of the depth data and an decorrelated portion of the depth data
135
End

Fig. 1A

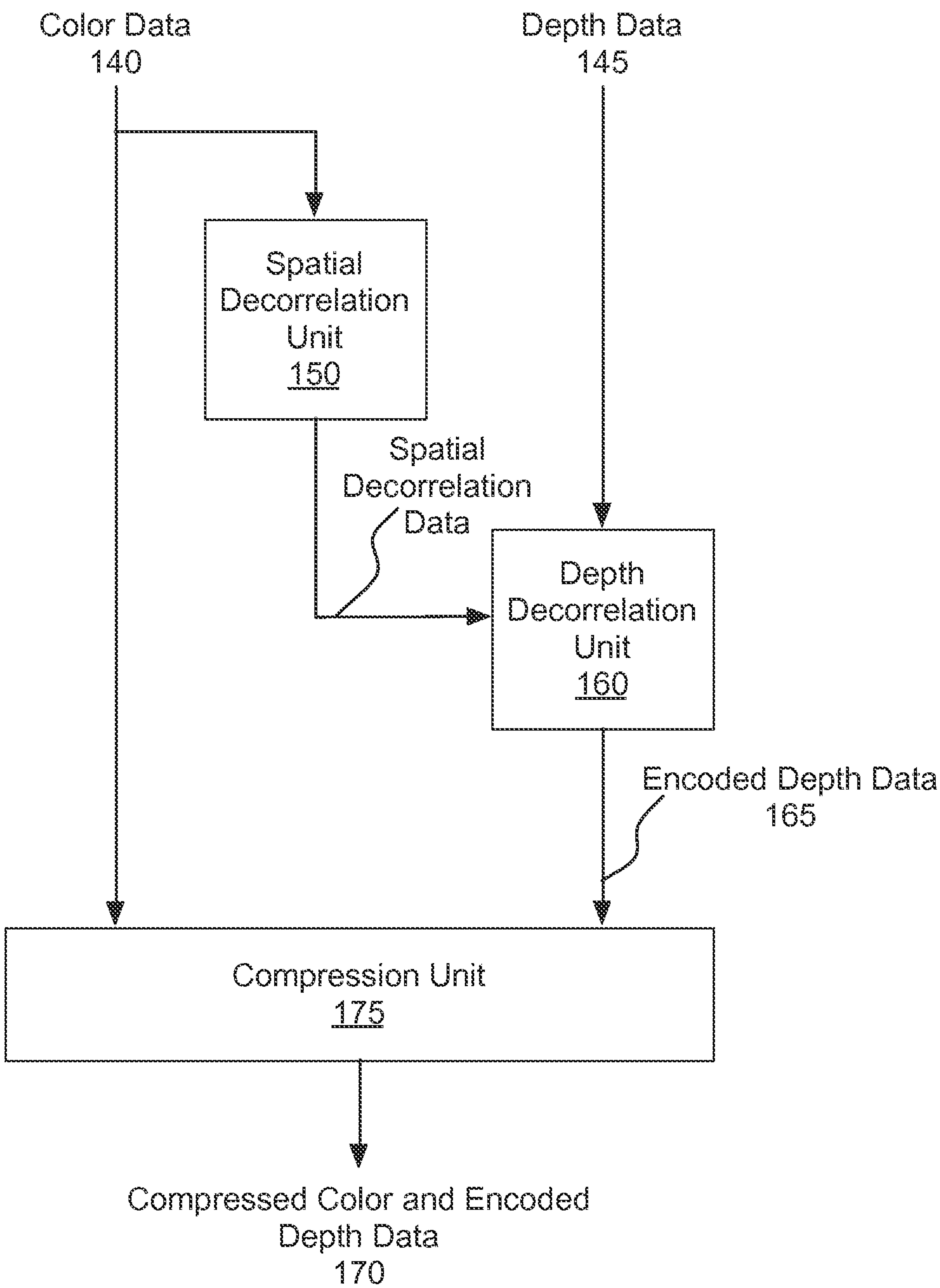
Color Data
140
Depth Data
145
Spatial
Decorrelation
Unit
150
Spatial
Decorrelation
Data
Depth
Decorrelation
Unit
160
Encoded Depth Data
165
Compression Unit
175
Compressed Color and Encoded
Depth Data
170

Fig. 1B

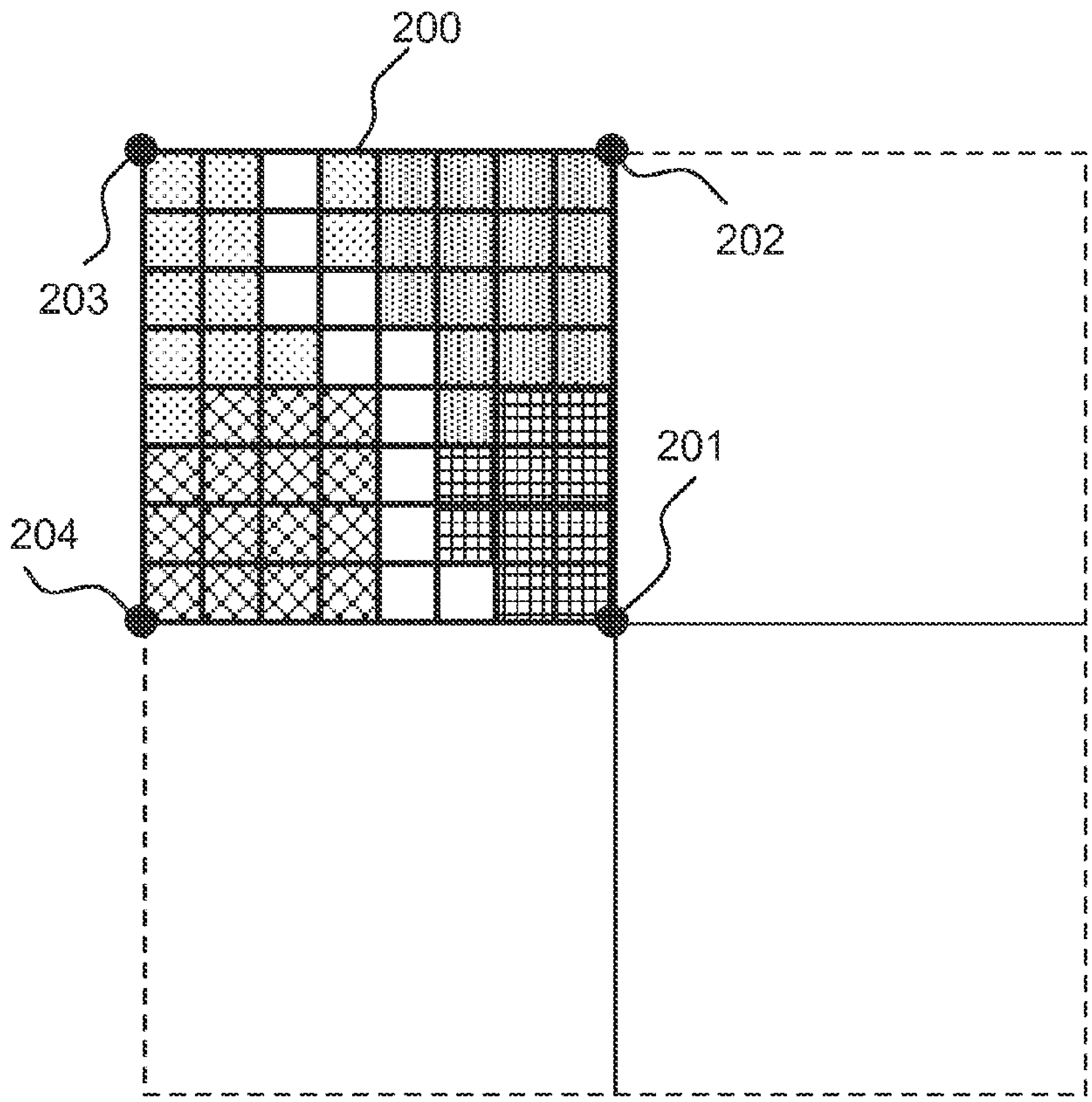

Fig. 2A

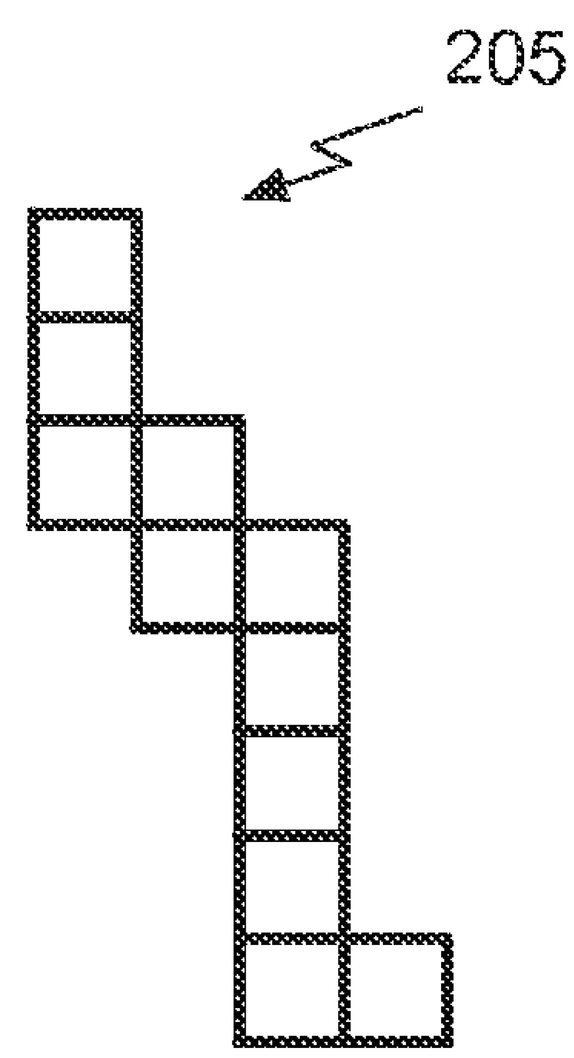

Fig. 2B

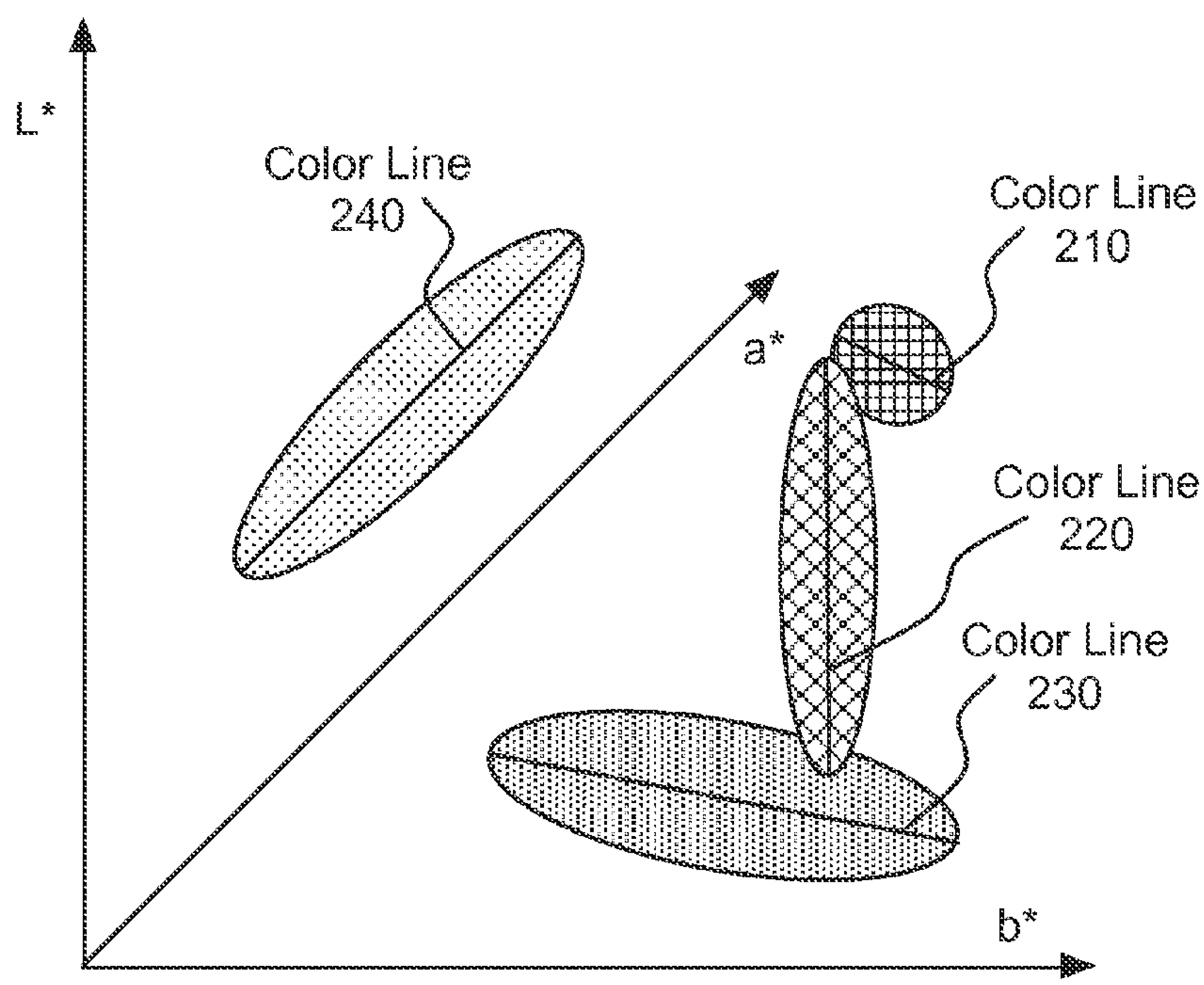

Fig. 2C

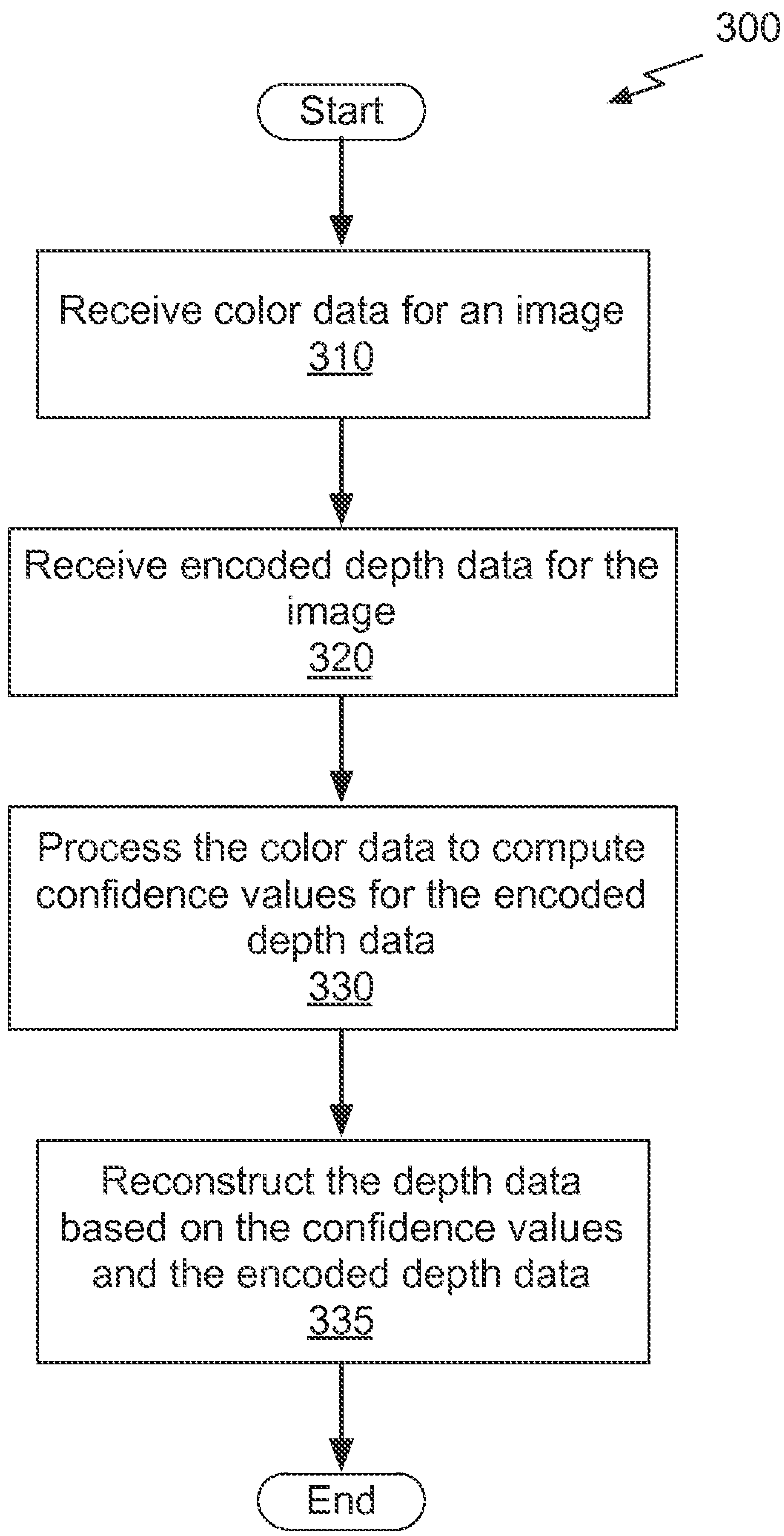
300
Start
Receive color data for an image
310
Receive encoded depth data for the image
320
Process the color data to compute confidence values for the encoded depth data
330
Reconstruct the depth data based on the confidence values and the encoded depth data
335
End

Fig. 3A

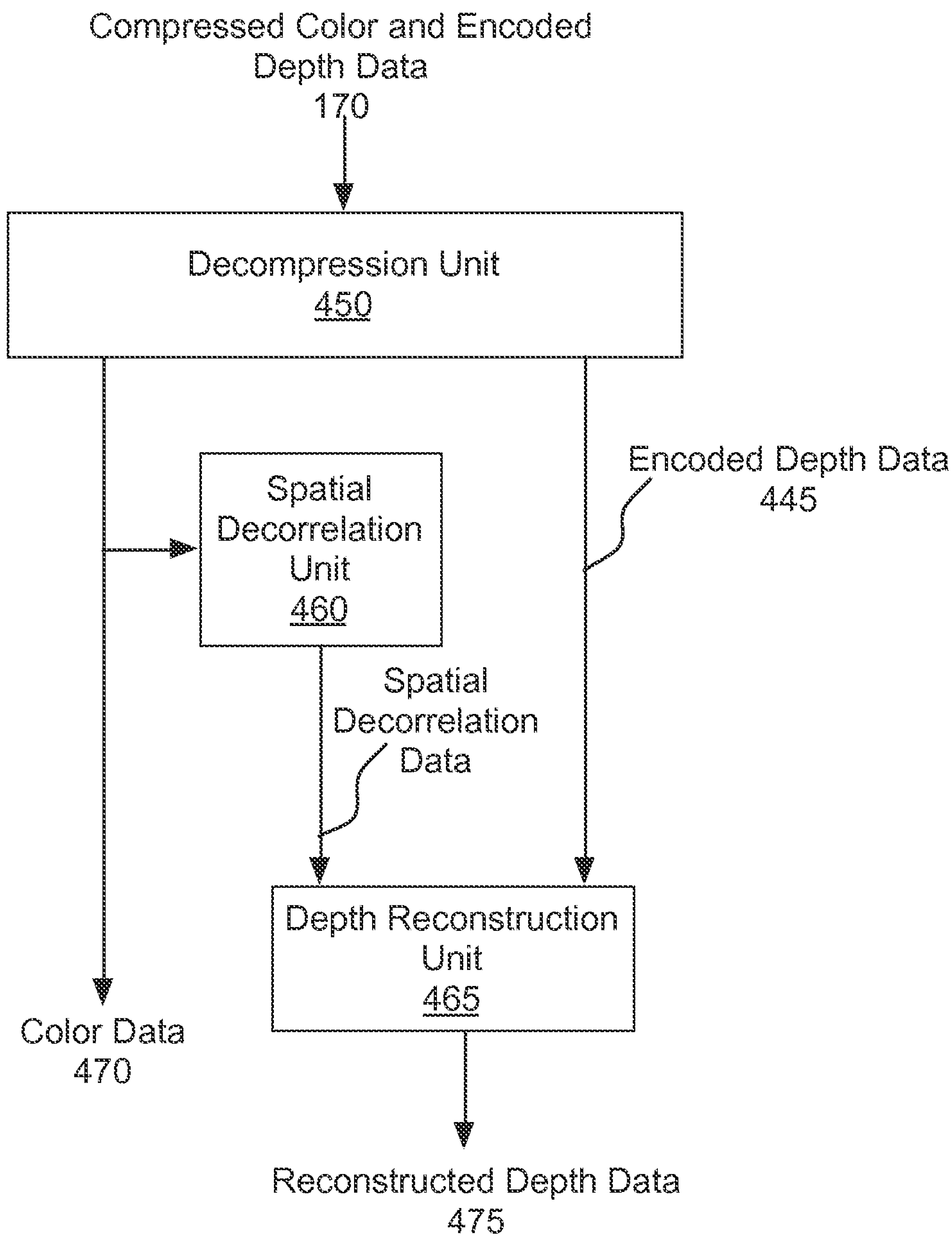
Compressed Color and Encoded Depth Data
170
Decompression Unit
450
Spatial Decorrelation Unit
460
Encoded Depth Data
445
Spatial Decorrelation Data
Depth Reconstruction Unit
465
Color Data
470
Reconstructed Depth Data
475

Fig. 3B

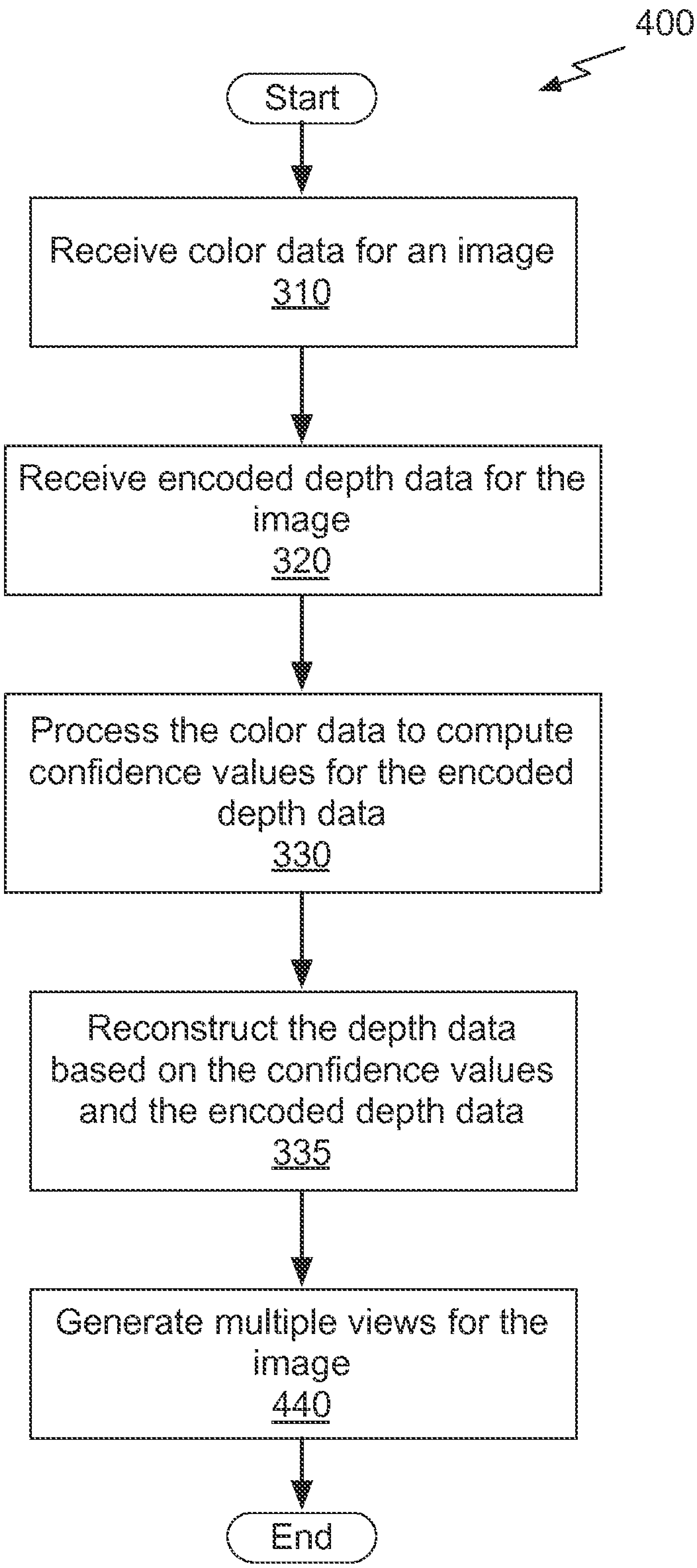
400
Start
Receive color data for an image
310
Receive encoded depth data for the image
320
Process the color data to compute confidence values for the encoded depth data
330
Reconstruct the depth data based on the confidence values and the encoded depth data
335
Generate multiple views for the image
440
End

Fig. 4

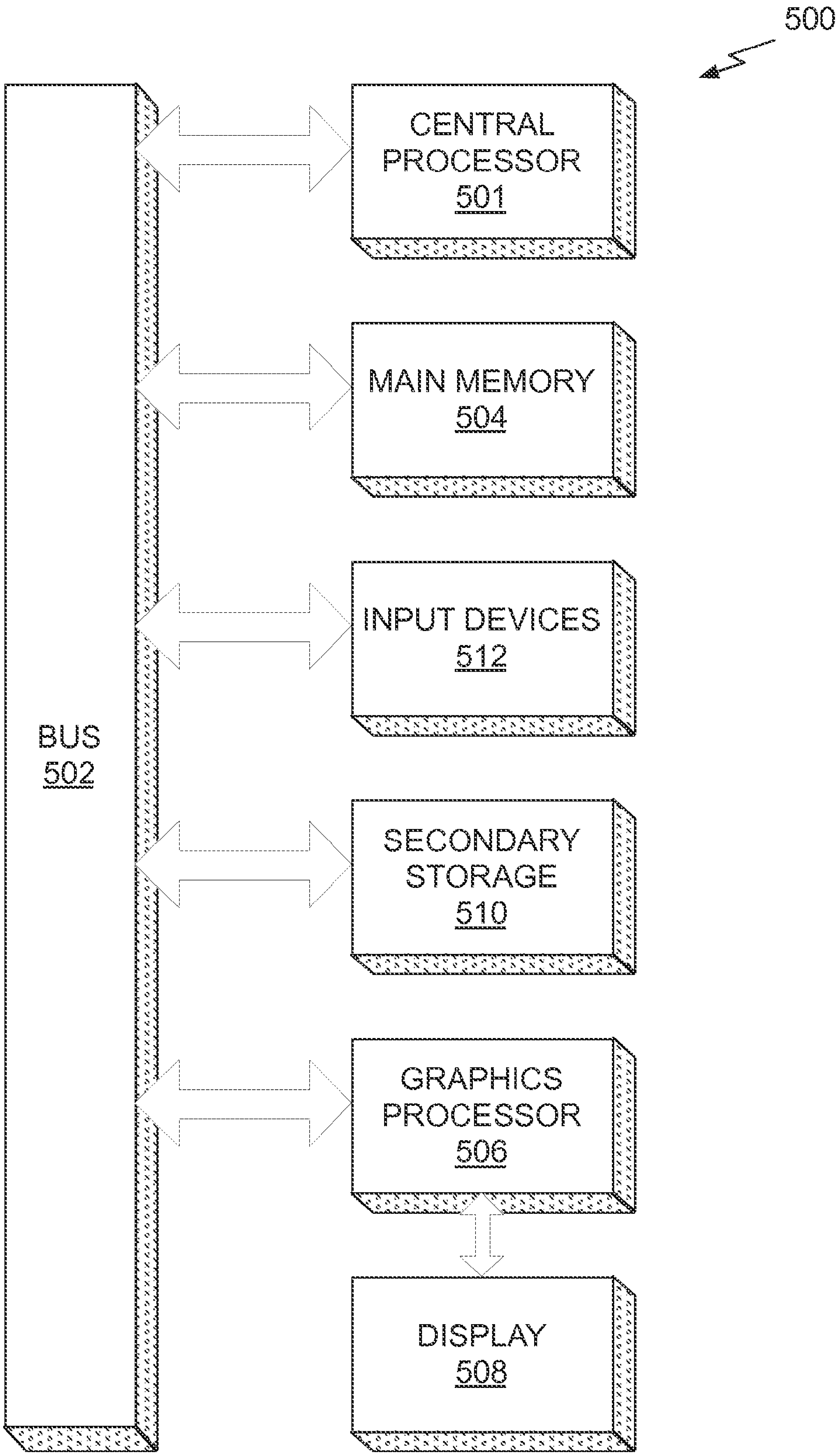
500
CENTRAL PROCESSOR 501
MAIN MEMORY 504
INPUT DEVICES 512
BUS 502
SECONDARY STORAGE 510
GRAPHICS PROCESSOR 506
DISPLAY 508

Fig. 5

SYSTEM, METHOD, AND COMPUTER PROGRAM PRODUCT FOR JOINT COLOR AND DEPTH ENCODING

CLAIM OF PRIORITY

This application claims the benefit of U.S. Provisional Application No. 61/883,917 titled "A Method of Joint Color and Depth Video Compression For Stereo Applications," filed Sep. 27, 2013, the entire contents of which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to data processing, and more specifically to joint color and depth data encoding.

BACKGROUND

State-of-the-art video coding standards, such as H.264 achieve high compression efficiency based on two important assumptions. First, the encoded data is assumed to come from spatially and temporally sampled natural (real world) scenes. Such signals are mostly continuous in space and, due to relatively high frame rates, the change of information from one frame to the next is usually small—it is mostly due to camera or object motion. Video encoders exploit this spatio-temporal redundancy by only encoding data that cannot be derived or predicted from spatial or temporal neighborhoods.

Unfortunately, compression tools that are designed with the above assumptions in mind are sub-optimal for depth coding. Their use, even in high-bandwidth scenarios, can lead to subpar three-dimensional (3D) video quality. Approaches specific to computer-graphics applications can be prohibitively expensive in terms of bandwidth requirements. Thus, there is a need for improving coding of depth data to improve compression rates and reduce the bandwidth needed to transmit the depth data.

SUMMARY

A system and method are provided for performing joint color and depth encoding. Color data and depth data for an image is received. Based on the color data, confidence values are computed for the depth data and the depth data is encoded based on the confidence values to represent a correlated portion of the depth data and a decorrelated portion of the depth data. In one embodiment, the depth data comprises per-pixel vergence angles.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A illustrates a flowchart of a method for performing joint color and data encoding, in accordance with one embodiment.

FIG. **1**B illustrates a block diagram for performing joint color and data encoding, in accordance with one embodiment.

FIG. **2**A illustrates a block of pixels of an image, in accordance with one embodiment.

FIG. **2**B illustrates decorrelated pixels within the block of pixels shown in FIG. **2**A, in accordance with one embodiment.

FIG. **2**C illustrates color lines corresponding to the pixels within the block of pixels shown in FIG. **2**A, in accordance with one embodiment.

FIG. **3**A illustrates a flowchart of a method for performing joint color and data decoding, in accordance with one embodiment.

FIG. **3**B illustrates a block diagram for performing joint color and data decoding, in accordance with one embodiment.

FIG. **4** illustrates a flowchart of a method for performing joint color and data decoding to generate multiple views of an image, in accordance with one embodiment.

FIG. **5** illustrates an exemplary system in which the various architecture and/or functionality of the various previous embodiments may be implemented.

DETAILED DESCRIPTION

Conventional depth video compression uses video codecs designed for color images. Given the performance of current encoding standards, this solution seems efficient. However, such an approach suffers from many issues stemming from discrepancies between depth and light perception. Because the depth may be well correlated with the color, the depth can be encoded and reconstructed on the decoder side using the color to produce 3D video with good quality in terms of both depth and color. The depth encoding technique can easily be integrated into existing encoders/decoders to significantly improve compression, and compression efficiency may be improved without sacrificing the visual quality of depth of rendered content, as well as the output of depth-reconstruction algorithms or depth cameras.

FIG. **1**A illustrates a flowchart of a method **100** for performing joint color and depth encoding. At operation **110**, color data is received. In one embodiment, a color value comprising three color components is received for each pixel in the image. The two or more separate channels may vary independently. In one embodiment, the color data is represented in an opponent color space. CIELAB color space is an opponent color space and RGB color space is not an opponent color space. The key property of an opponent color space is a statistical decorrelation of color channels, which allows an encoder to compress the color channels independently and focus the encoding on perceptually significant information.

At operation **120**, depth data for the image is received. In one embodiment, the depth data is represented as per-pixel vergence angles. A vergence angle is used in stereo applications and can be considered a measure of physically (and perceptually) significant depth. More specifically, a vergence angle is the angle between two ray where the first ray starts at a point on an object and ends at a viewer's left eye and the second ray starts at the point and ends at the viewer's right eye. Thus, a smaller vergence angle corresponds to increased distance from the viewer (i.e., increased depth) and a larger vergence angle corresponds to decreased distance from the viewer (i.e., decreased depth). Vergence angles may be considered to be depth values or depth data for the purposes of the following description. The depth data may be represented in a fixed-point format or in a floating-point format. The color data and/or the depth data may be stored in a memory.

At operation **130**, based on the color data, confidence values are computed for the depth data. In one embodiment, the per-pixel color data C for the image is sampled at one position in a k×k block and the confidence values indicate how well the sampled color data represents each color data C inside the k×k block. In one embodiment, k≥4. For example, when color values in a 4×4 block do not vary or vary only by a small amount, a single sampled color value is a good representation of the color values of all of the pixels in the k×k block. A high confidence value indicates correlation between the sampled color data and the color data and a low confidence value indicates decorrelation between the sampled color data and the color data.

In one embodiment, depth data D for an image having a width and height is downsampled by a factor k in width and height to generate sampled depth data. For example, a depth value for a single pixel in a block of pixels may be selected as the sampled depth data for a block of pixels. Assuming $\hat{d}$ represents sampled depth data for an image, when k=4, each depth value in $\hat{d}$ represents a 4×4 block of depth values of D. Formally, $\hat{d}(i):=D(k\cdot i)$, where I(i) is the pixel value of an image I at pixel position i. The sampled depth data and/or the color data may be stored in a memory. Because the depth values tend to correspond to the color values, the confidence values generated based on the sampled color data also indicate correlation and decorrelation between the sampled depth data $\hat{d}$ and the depth data D.

In addition to computing confidence values for the sampled color data for the particular k×k block, at operation **130** confidence values are computed using the sampled color data of neighboring k×k blocks. In one embodiment, for each pixel in the k×k block, additional confidence values are computed using the sampled color data for 3 neighboring k×k blocks, when the particular k×k block and the 3 neighboring k×k blocks form a larger 2k×2k block. The depth data for each pixel in the k×k block may then be defined as a weighted average of sampled depth data for the particular k×k block and sampled depth data for the neighboring k×k blocks, where the weights for each pixel are the confidence values that are computed based on the color data.

At operation **135**, the depth data is encoded based on the confidence values to represent a correlated portion of the depth data and a decorrelated portion of the depth data. The correlated portion of the depth data for a block of pixels is represented by the sampled depth value for the block. A first approximation of the depth data for the block of pixels may be reconstructed using the sampled depth value and the confidence values. However, some details in the block may not be represented by the sampled depth value and the confidence values. The decorrelated portion of the depth data for the block of pixels is represented by a different depth value that corresponds to the details. In one embodiment, the decorrelated portion of the depth data is represented by a residual depth value. In one embodiment, the sampled depth data $\hat{d}$ for each block of an image are inserted into a first component channel and residual depth values for each block of the image are inserted into a second component channel. The component channels may be two color component channels.

In one embodiment, the residual depth value may be computed based on the confidence values $w_{sum}(j)$. First, the confidence values are used to compute complementary confidence values $w_c(j)$ that indicate decorrelation between the sampled color data and the color data. Second, the complementary confidence values are used to compute a representative decorrelated depth value as a weighted sum of the per-pixel depth data for the block, where the weight used for each pixel's depth value is the complementary confidence value $w_c(j)$. In one embodiment, the residual depth value for a block is then computed as a difference between the sampled depth value and the representative decorrelated depth value of the depth data. Thus, in one embodiment, the encoded depth data **165** for a block is two values (e.g., a single sampled depth value and the residual depth value) compared with k×k depth values prior to encoding.

More illustrative information will now be set forth regarding various optional architectures and features with which the foregoing framework may or may not be implemented, per the desires of the user. It should be strongly noted that the following information is set forth for illustrative purposes and should not be construed as limiting in any manner. Any of the following features may be optionally incorporated with or without the exclusion of other features described.

FIG. **1**B illustrates a block diagram for performing joint color and data encoding, in accordance with one embodiment. Color data **140** is input to a spatial decorrelation unit **150** and a compression unit **175**. In one embodiment, the spatial decorrelation unit **150** is configured to sample the color data **140** to produce a sampled color value for each block of pixels and to generate per-pixel confidence values based on the color data **140** and the sampled color values. The confidence values for a block of pixels may be used to identify the pixels that are correlated in terms of color data and the pixels that are decorrelated in terms of color data. The complementary confidence values for the block of pixels may be computed based on the confidence values for the block of pixels. Additionally, a complementary confidence mask may be computed for the block of pixels based on the complementary confidence values. The complementary confidence mask indicates the particular pixels in the block having decorrelated color data. In other words, the complementary confidence mask indicates any pixels in the block that have low confidence values and whose color or depth value cannot be accurately reconstructed from the sampled color value or sampled depth value, respectively. As previously explained, the pixels which are decorrelated in terms of color are assumed to be decorrelated in terms of depth.

The spatial decorrelation data that is output by the spatial decorrelation unit **150** includes at least one of the confidence values, the complementary confidence mask, and the complementary confidence values $w_c(j)$ for each block of pixels. Importantly, in one embodiment, the spatial decorrelation data is generated using only the color data. In one embodiment, the spatial decorrelation data that is output to the depth decorrelation unit **160** is only the confidence values that are needed to generate the residual depth value for each block of pixels. In another embodiment, the spatial decorrelation data that is output to the depth decorrelation unit **160** is only the complementary confidence values that are needed to generate the residual depth value for each block of pixels.

In one embodiment, the compression unit **175** outputs the color data without compressing the color data as a color portion of the compressed color and encoded depth data **170**. In another embodiment, the compression unit **175** is configured to compress the color data to produce the color portion of the compressed color and encoded depth data **170**. Persons skilled in the art will understand that one or more known compression techniques, such as H.264 may be employed by the compression unit **175**.

Depth data **145** is input to the depth decorrelation unit **160**. In one embodiment, the depth decorrelation unit **160** is configured to downsample the depth data **145** to produce sampled depth data as a correlated portion of the encoded depth data **165**. In one embodiment, a single sampled depth value is produced for each block of pixels. The depth decorrelation unit **160** also receives the spatial decorrelation data corresponding to the color data **140** from the spatial decorrelation unit **150**. The depth decorrelation unit **160** computes the residual depth value for the block using the depth data, the sampled depth value, and the spatial decorrelation data and outputs the residual depth value as a decorrelated portion of the encoded depth data **165**. The encoded depth data **165** that is output by the depth decorrelation unit **160** includes the residual depth values and the sampled depth values.

In one embodiment, the compression unit **175** is configured to output the encoded depth data **165** as a depth portion of the compressed color and encoded depth data **170** that is output by the compression unit **175**. In another embodiment, the compression unit **175** is configured to compress the encoded depth data **165** to produce the depth portion of the compressed color and encoded depth data **170**.

One or more of the spatial decorrelation unit **150**, depth decorrelation unit **160**, and compression unit **175** may be included within a processing unit. The functions performed by one or more of the spatial decorrelation unit **150**, depth decorrelation unit **160**, and compression unit **175** may be performed by a general purpose processing unit or dedicated circuitry. One or more of the color data **140**, depth data **145**, spatial decorrelation data, encoded depth data **165**, sampled depth data, and compressed color and encoded depth data **170** may be stored in a memory.

FIG. **2**A illustrates a block of pixels **200** of an image, in accordance with one embodiment. A color image C (i.e., color values for the image) is partitioned into blocks C_i. Similarly, a depth image D (i.e., depth values for the image), of resolution $d_{width} \times d_{height}$, is partitioned into blocks D_i. A block with index $i \in \{(x,y) \in Z^2: 0 \le x < \lfloor d_{width}/k \rfloor \Lambda 0 \le y < \lfloor d_{height}/k \rfloor$ represents the pixels $\{k \cdot i+(x,y):(x,y) \in Z^2, 0 \le x < k \wedge 0 \le y < k\}$ of the image. The Depth image D may be reconstructed block by block using the spatial decorrelation data generated using only the color data and the encoded depth data **165**, as described further herein.

As shown in FIG. **2**A, the block of pixels **200** is 8×8 pixels, so k=8. Each pattern represents a different color. When the image is partitioned into blocks, a sampled color and a sampled depth value is computed for each block of pixels **200**. For example, a sampled depth value and a sampled color value for the block of pixels **200** may be associated with a position **203** in the upper left corner of the block of pixels **200**. Sampled depth values and Sampled color values that are computed for neighboring blocks of pixels may be associated with positions **202**. **203**, and **204**. Thus, there are four sampled color values available to generate the spatial decorrelation data and four sampled depth values available to reconstruct the depth values of individual pixels in the block of pixels **200**. Specifically, the sampled depth values associated with the positions **201**, **202**, **203**, and **204** may be used to reconstruct the depth values for the block of pixels **200**.

An approximation of the depth data for each pixel in the block of pixels **200** may be reconstructed as a weighted function of the sampled depth values associated with the positions **201**, **202**, **203**, and **204**. However, small features inside the block of pixels **200** may not always be well represented by the sampled depth values associated with the positions **201**, **202**, **203**, and **204**. The spatial decorrelation data that are generated from the color data for the block of pixels **200** may indicate decorrelated pixels corresponding to small features that may not be well represented. The residual depth value for each block of pixels provides additional information to reconstruct the depth data for the decorrelated pixels.

As shown by the patterns in FIG. **2**A, colors of the pixels in the upper left corner of the block of pixels **200** correlates with a color value at the position **203**, colors of the pixels in the lower left corner of the block of pixels **200** correlates with the color value at the position **204**, colors of the pixels in the upper right corner of the block of pixels **200** correlates with the color value at the position **202**, and colors of the pixels in the lower right corner of the block of pixels **200** correlates with the color value at the position **201**.

FIG. **2**B illustrates decorrelated pixels **205** within the block of pixels **200** shown in FIG. **2**A, in accordance with one embodiment. In the example shown in FIG. **2**A, the decorrelated pixels **205** do not correlate with any combination of the color values at positions **201**, **202**, **203**, and **204**. The decorrelated pixels **205** may be indicated by a complementary confidence mask. During encoding, a representative decorrelated depth value and residual depth value may be computed to represent the decorrelated pixels **205**. The residual depth value for the block of pixels **200** may be computed as the difference between the sampled depth value associated with the position **203** and the representative decorrelated depth value. Thus, a residual depth value is associated with each sampled depth value. During reconstruction of the depth data, the residual depth value and the spatial decorrelated data may be used to reconstruct depth values for the pixels indicated by the complementary confidence mask.

The residual depth value provides one additional sampled depth value for each block of pixels **200**. In one embodiment, more than one additional sampled depth value is provided for each block of pixels **200** by encoding additional residual depth values that represent other decorrelated portions of the depth data for the block of pixels **200**.

FIG. **2**C illustrates color lines corresponding to correlated pixels within the block of pixels **200** shown in FIG. **2**A, in accordance with one embodiment. The color value for each pixel in the block of pixels **200** may be mapped to a CIELAB color space having coordinates L*, a*, and b*. Color values for pixels that are correlated form clusters. In many cases, the color value at a position p within a block of pixels can be quite different from neighboring pixels, even when the same surface covers the neighboring pixels. However, local image structures tend to exhibit large variations only in one specific color channel (e.g., brightness), but gradual changes in other color channels, producing the color lines. The color lines may be used to determine a better range weighting to reconstruct the depth values of the image.

A color line may be computed as the first eigenvector over weighted pixel distribution in the CIELAB color space. Each of the four downsampled color values in the block of pixels **200** corresponds to a color line (i.e., first eigenvector) shown in FIG. **2**C. Each color line **210**, **220**, **230**, and **240** is positioned along the major axis of a cluster of pixel colors. The pixel colors associated with each color line lie within the oblong shape surrounding the respective color line. For example, the color line **240** corresponds to the sampled color value **203** in the upper left corner of the block of pixels **200**. The color line **210** corresponds to the sampled color value **201** in the lower right corner of the block of pixels **200**. The color line **220** corresponds to the sampled color value **204** in the lower left corner of the block of pixels **200**. The color line **230** corresponds to the sampled color value **202** in the upper right corner of the block of pixels **200**. The decorrelated pixels **205** indicated by the complementary confidence mask do not correspond to one of the color lines **210**, **220**, **230**, or **240**. The representative decorrelated depth value computed for the decorrelated pixels **205** effectively corresponds to an additional color line (not shown in FIG. **2**C).

In one embodiment, local color line model (LCLM) is introduced where an anisotropic distance function is derived for a position p based on the color-line orientation. The anisotropic distance describes the individual pixel colors more accurately than a standard uniform distance. An approximation of a PCA of the color values in CIELAB color space is computed in an k×k-pixel neighborhood around p. Using the inverse of the eigenvalues along the axis defined by the eigenvectors, leads to a distance that is virtually shrunk along the color line.

Instead of computing a full principal component analysis (PCA), a more efficient approximation may be computed by deriving the first eigenvector of the PCA via a power iteration method. The first eigenvector is described by $Q_{n+1}=MQ_n/\|MQ_n\|$, where M is the covariance matrix and Q is the current eigenvector estimate. Three iterations are usually sufficient to find the first eigenvector, and, hence, its eigenvalue λ_p. We then define

$$\Lambda := \begin{pmatrix} \lambda_p & 0 & 0 \\ 0 & \sigma_2^2 & 0 \\ 0 & 0 & \sigma_2^2 \end{pmatrix},$$

where σ_2^2 is the variance of the pixel colors distances to the line defined by the eigenvector and average color μ_p. Next, we set $T_p^{-1}:=V_p \Lambda_p^{-1} V_p^T$, where V_p is an orthogonal matrix containing the first eigenvector in the first row. T_p^{-1} is then used in the definition of the confidence value (i.e., weighting function) h_p by involving the Mahalanobis distance

$$h_p(X) := e^{-\left(\sigma_c^{-1}\sqrt{(X-\mu_p)^T T_p^{-1}(X-\mu_p)}\right)^2},$$

where σ_c is a constant that controls the tradeoff with respect to the spatial weighting function (in one embodiment, 0.1 is used for all examples). The confidence value h_p (X) is computed for each pixel (e.g., pixel at position X) inside the block p and is defined as a distance metric of a pixel color to local color line model that characterizes color data of the sample position within block p. With this construction, the color lines are assumed to have a shape in color space that is rotationally invariant around a center line. Further, the full PCA computation is avoided which makes the technique very fast to compute.

In one embodiment, robustness and quality are increased even further by excluding outliers when estimating each color line. When blocks of pixels contain several boundaries of significantly different surfaces, there may be more outliers. In one embodiment, a weighted power iteration may be used when determining Q, λ_p, and μ_p to exclude the outliers (i.e., decorrelated pixels). In other words, each pixel contributes differently to the color line and is weighted based on distance to the color line and similarity to p. The standard bilinear-filter weights may be used, with the same weighting function w for spatial weighting and an exponential falloff with a sigma of 1.0 for range weighting. In one embodiment, the weighting function w is a simple unit "pyramid"-filter kernel. In other embodiments, other isotropic kernels are used for the weighting function. A large range sigma makes sure that only extreme outliers (e.g., decorrelated portion of the color and depth data) are excluded for the color line estimation. A fifth color line may be computed for the outliers using the per-pixel complementary confidence values $wc_i(i)=e^{-(\sigma_c^{-1} w_{sum}(j))^2}$.

The depth values for each block of pixels of the image may be reconstructed based on the color data, the sampled depth data $\hat{d}$, and residual depth values $\hat{d}^c$ that represent the decorrelated portion of depth data in each block of pixels.

FIG. **3**A illustrates a flowchart of a method **300** for performing joint color and data decoding, in accordance with one embodiment. At operation **310**, color data is received for an image. In one embodiment, the color data may be color data that has been compressed and then decompressed (when lossless compression is used) to reproduce the color data. At operation **320**, encoded depth data is received for the image.

At operation **330**, the color data is processed to compute confidence values $w_{sum}(j)$ for the encoded depth data. As previously explained, the confidence values may be used to compute the complementary confidence values $wc_i(j)$ that were used during encoding. The complementary confidence mask that was used to identify decorrelated pixels for a particular block during encoding may be regenerated to identify the same decorrelated pixels for the block during decoding. At operation **335**, the depth data is reconstructed based on the spatial decorrelation data (e.g., confidence values, complementary confidence values, and/or the complementary confidence mask) and the encoded depth data.

In one embodiment, the depth data D may be reconstructed using only the sampled depth values without using the residual depth values $\hat{d}^C$. When the depth data D is reconstructed using only the sampled depth values without using the residual depth values, a block D_i may be approximated by a reconstruction D_i', which is defined via a weighted average of four pixel values $\hat{d}$ that are associated with the positions **201**, **202**, **203**, and **204** of the block of pixels **200** (D_i). For every output pixel, the weights are recomputed based on weighting functions determining color similarity h_p and spatial proximity (weighting function) w. In one embodiment, the reconstruction is defined by:

$$D_i'(j) = \frac{\sum_{p\in\Omega_i} w((p-i)-j/k)\cdot h_p(C_i(j))\cdot \hat{d}(p)}{w_{sum}(j)},$$

where $\Omega_i:=\{i, i+(1,0), i+(0,1), i+(1,1)\}$ and $w_{sum}(j):=w((p-i)-j/k)\cdot h_p(C_i(j)), j\in\{(x,y)\in Z: 0\le x<k \wedge 0\le j<k\}$. Importantly, a complex definition of the range weighting h_p, estimates the likelihood that a given color belongs to the surface underneath pixel p.

The reconstruction may be modified to also use the residual depth values to reconstruct the depth data more accurately:

$$D_i^C(j) = \frac{w_{sum}(j)D_i'(j) + wc_i(j)\hat{d}^C(i)}{w_{sum}(j) + wc_i(j)},$$

where the residual depth values $\hat{d}^C$ are an additional image representing the decorrelated portion of the depth data that is encoded with $\hat{d}$ and $w_{ci}(j)$ is the complementary confidence values for each block of pixels. The optimal value of $\hat{d}^C(i)$ may be computed by minimizing the difference between the depth data and the reconstructed depth data. $|D_i-D_i^C|$.

It may be surprising that a low-resolution stream of encoded depth data is sufficient to reconstruct high-quality depth, yet it can be well motivated. For image/video coding the typical size of 8×8 pixels for a discrete cosine transform (DCT) block matches well the human visual system contrast sensitivity in color vision, which roughly ranges from 1 to 50 cpd (cycles per degree). A typical display device shows signals with up to 20 cpd. Therefore, an 8×8 pixel DCT block is best at encoding luminance in the range of 2.5 cpd corresponding to the lowest frequency AC coefficient (half a cycle per block) to 20 cpd (highest frequency AC coefficient). However, the HVS frequency-sensitivity to depth/disparity is much lower and ranges from 0.3 cpd to 5 cpd. Therefore, an 8-pixel-wide block not only encodes very low frequencies badly, but also wastes information by encoding frequencies above 5 cpd that do not improve the perceived stereo quality (when depth is used to produce stereo images). Consequently, it may be possible to downsample the depth image by a factor of k=4 before encoding the depth data, thereby targeting frequencies in the range from 0.625 to 5 cpd.

However, humans also tend to be sensitive to phase in the presence of edges. Therefore, similar to luminance, more precision is needed for isolated disparity edges. Therefore, the reconstructing of the encoded depth data using the confidence values improves the quality of the recovered depth data since the high-frequency depth edges may be recovered from the high-resolution color image. Furthermore, if depth edges are not matched by color edges in natural stereo images, the depth edges are unlikely to be perceived by a viewer.

FIG. **3**B illustrates a block diagram for performing joint color and data decoding, in accordance with one embodiment. A decompression unit **450** receives the compressed color and encoded depth data **170**. In one embodiment, the decompression unit **450** is configured to decompress the depth portion of the compressed color and encoded depth data and output the encoded depth data including the sampled depth data (correlated portion of the depth data) and the residual depth values (decorrelated portion of the depth data) to a depth reconstruction unit **465**. In one embodiment, the decompression unit **450** is configured to decompress the color portion of the compressed color and encoded depth data and output the color data **470**. Persons skilled in the art will understand that one or more known decompression techniques may be employed by the decompression unit **450**.

The color data **470** is processed by a spatial decorrelation unit **460** to produce spatial decorrelation data corresponding to the color data **470**. In one embodiment, the spatial decorrelation data includes confidence values for the pixels in each block. In one embodiment, the spatial decorrelation data includes complementary confidence values indicating any pixels that have low confidence values. Importantly, in one embodiment, the spatial decorrelation data is generated using only the color data. The complementary confidence mask corresponding to the complementary confidence values indicates pixels whose color or depth value cannot be accurately reconstructed from the sampled color or depth data, respectively.

The depth reconstruction unit **465** receives the encoded depth data from the decompression unit **450** and spatial decorrelation data corresponding to the color data from the spatial decorrelation unit **460**. The depth reconstruction unit **465** computes the representative decorrelated depth value and reconstructed depth values for pixels. The depth reconstruction unit **465** outputs the reconstructed depth values **475**.

One or more of the decompression unit **450**, spatial decorrelation unit **460**, and depth reconstruction unit **465** may be included within a processing unit. The functions performed by one or more of the decompression unit **450**, spatial decorrelation unit **460**, and depth reconstruction unit **465** may by performed by a general purpose processing unit or dedicated circuitry. One or more of the color data **470**, reconstructed depth data **475**, encoded depth data, sampled depth data, spatial decorrelation data, and compressed color and encoded depth data **170** may be stored in a memory.

FIG. **4** illustrates a flowchart of a method **400** for performing joint color and data decoding to generate multiple views of an image, in accordance with one embodiment. Operations **310**, **320**, **330**, **335** are performed as previously described in conjunction with FIG. **3**A. When stereo viewing applications are supported, multiple views are needed for each image. Existing systems may encode multiple views for each image and the view that is best suited to the viewing environment may be decoded for display. The viewing environment may include one or more of the resolution and/or screen size of the viewing device, the viewing distance, characteristics of the viewer (e.g., distance between eyes), content (e.g., extent of the scene and visible objects), and the like. Representing the depth data as per-pixel vergence angles allows for the construction of multiple views using the reconstructed depth data. At operation **440**, multiple views for stereo applications (e.g., 3DTV) are generated for the image using the reconstructed depth data. The multiple views for an image may be generated using a single reconstructed depth data corresponding to the image. Therefore, the bandwidth requirements for the encoded color and depth data are reduced compared with transmitting multiple views of the image.

The encoding technique described in conjunction with FIGS. **1**A, **1**B, **2**A, **2**B, and **2**C represents high quality depth data. The color-based depth reconstruction that is used to reconstruct the depth data is robust even for larger subsampling ratios (e.g., k=16). Also, the sampled depth data may be efficiently compressed. The depth encoding technique may be integrated into existing encoders to improve compression ratios and the quality of reconstructed depth data for images.

FIG. **5** illustrates an exemplary system **500** in which the various architecture and/or functionality of the various previous embodiments may be implemented. As shown, a system **500** is provided including at least one central processor **501** that is connected to a communication bus **502**. The communication bus **502** may be implemented using any suitable protocol, such as PCI (Peripheral Component Interconnect), PCI-Express. AGP (Accelerated Graphics Port), HyperTransport, or any other bus or point-to-point communication protocol(s). The system **500** also includes a main memory **504**. Control logic (software) and data are stored in the main memory **504** which may take the form of random access memory (RAM).

The system **500** also includes input devices **512**, a graphics processor **506**, and a display **508**, e.g., a conventional CRT (cathode ray tube), LCD (liquid crystal display). LED (light emitting diode), plasma display or the like. User input may be received from the input devices **512**, e.g., keyboard, mouse, touchpad, microphone, and the like. In one embodiment, the graphics processor **506** may include a plurality of shader modules, a rasterization module, etc. Each of the foregoing modules may even be situated on a single semiconductor platform to form a graphics processing unit (GPU).

In the present description, a single semiconductor platform may refer to a sole unitary semiconductor-based integrated circuit or chip. It should be noted that the term single semiconductor platform may also refer to multi-chip modules with increased connectivity which simulate on-chip operation, and make substantial improvements over utilizing a conventional central processing unit (CPU) and bus implementation. Of course, the various modules may also be situated separately or in various combinations of semiconductor platforms per the desires of the user.

The system **500** may also include a secondary storage **510**. The secondary storage **510** includes, for example, a hard disk drive and/or a removable storage drive, representing a floppy disk drive, a magnetic tape drive, a compact disk drive, digital versatile disk (DVD) drive, recording device, universal serial bus (USB) flash memory. The removable storage drive reads from and/or writes to a removable storage unit in a well-known manner. Computer programs, or computer control logic algorithms, may be stored in the main memory **504** and/or the secondary storage **510**. Such computer programs, when executed, enable the system **500** to perform various functions. The main memory **504**, the storage **510**, and/or any other storage are possible examples of computer-readable media.

In one embodiment, the architecture and/or functionality of the various previous figures may be implemented in the context of the central processor **501**, the graphics processor **506**, an integrated circuit (not shown) that is capable of at least a portion of the capabilities of both the central processor **501** and the graphics processor **506**, a chipset (i.e., a group of integrated circuits designed to work and sold as a unit for performing related functions, etc.), and/or any other integrated circuit for that matter.

Still yet, the architecture and/or functionality of the various previous figures may be implemented in the context of a general computer system, a circuit board system, a game console system dedicated for entertainment purposes, an application-specific system, and/or any other desired system. For example, the system **500** may take the form of a desktop computer, laptop computer, server, workstation, game consoles, embedded system, and/or any other type of logic. Still yet, the system **500** may take the form of various other devices including, but not limited to a personal digital assistant (PDA) device, a mobile phone device, a television, etc.

Further, while not shown, the system **500** may be coupled to a network (e.g., a telecommunications network, local area network (LAN), wireless network, wide area network (WAN) such as the Internet, peer-to-peer network, cable network, or the like) for communication purposes.

While various embodiments have been described above, it should be understood that they have been presented by way of example only, and not limitation. Thus, the breadth and scope of a preferred embodiment should not be limited by any of the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents.

What is claimed is:

1. A method, comprising:
- receiving color data for an image;
- receiving depth data for the image;
- computing confidence values for the depth data based on the color data;
- computing, based on the confidence values, complementary confidence values corresponding to a decorrelated portion of the depth data;
- determining a representative decorrelated depth value corresponding to the decorrelated portion of the depth data; and
- computing a residual value as a difference between the representative decorrelated depth value and a sampled depth value for a block of pixels within the image; and
- encoding the depth data based on the confidence values to represent a correlated portion of the depth data and the decorrelated portion of the depth data.

2. The method of claim **1**, wherein the confidence values indicate correlations between the depth data and a sampled depth value for each pixel of the image.

3. The method of claim **1**, wherein encoding the depth data further comprises inserting the residual value into a first component channel and inserting the sampled depth value into a second component channel.

4. The method of claim **1**, wherein the depth data comprises per-pixel vergence angles.

5. The method of claim **1**, wherein the color data is represented in an opponent color space.

6. The method of claim **1**, further comprising compressing the encoded depth data.

7. The method of claim **1**, wherein computing confidence values comprises:
- mapping the color data to a color space; and
- computing a first eigenvector over a weighted pixel distribution in the color space as a color line associated with a correlated portion of the color data.

8. The method of claim **7**, further comprising computing an additional color line corresponding to a decorrelated portion of the color data.

9. The method of claim **1**, further comprising determining, based on the confidence values, a complementary confidence mask that indicates pixels in a block of pixels that are decorrelated based on the color data.

10. A method, comprising:
- receiving color data for an image;
- receiving encoded depth data that represents a correlated portion of depth data and a decorrelated portion of the depth data for the image;
- computing confidence values for the encoded depth data based on the color data;
- computing, based on the confidence values, complementary confidence values corresponding to the decorrelated portion of the depth data; and
- determining a representative decorrelated depth value corresponding to the decorrelated portion of the depth data based on a residual value that represents the decorrelated portion of the depth data and a sampled depth value that represents the correlated portion of the depth data for a block of pixels within the image; and
- reconstructing the depth data based on the confidence values and the encoded depth data.

11. The method of claim **10**, wherein the confidence values indicate correlations between the color data and sampled color data for each pixel of the image.

12. The method of claim **10**, wherein the residual value is included in a first component channel of the encoded depth data and the sampled depth data is included in a second component channel of the encoded depth data.

13. The method of claim **10**, wherein the reconstructed depth data comprises per-pixel vergence angles.

14. The method of claim **10**, wherein the color data is represented in an opponent color space.

15. The method of claim **10**, wherein computing confidence values comprises:
- mapping the reconstructed color data to a color space; and
- computing a first eigenvector over a weighted pixel distribution in the color space as a color line associated with a correlated portion of the color data.

16. The method of claim **15**, further comprising computing an additional color line corresponding to a decorrelated portion of the color data.

17. The method of claim **10**, further comprising determining, based on the confidence values, a complementary confidence mask that indicates pixels in a block of pixels that are decorrelated based on the color data.

18. A system, comprising:
- a memory configured to store color data for an image and depth data for the image; and
- a processing unit coupled to the memory and configured to:
  - receive the color data for the image;
  - receiving the depth data for the image;
  - compute confidence values for the depth data based on the color data;
  - compute, based on the confidence values, complementary confidence values corresponding to a decorrelated portion of the depth data;

determine a representative decorrelated depth value corresponding to the decorrelated portion of the depth data; and

compute a residual value as a difference between the representative decorrelated depth value and a sampled depth value for a block of pixels within the image; and

encode the depth data based on the confidence values to represent a correlated portion of the depth data and the decorrelated portion of the depth data.

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